

ELECTROWEAK BARYOGENESIS IN A SUPERSYMMETRIC MODEL TO APPEAR IN HEP95 PROCEEDINGS, BRUSSELS, 1995.

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1 Introduction and Formalism of the NMSSM

It is well known that there is difficulty in sustaining the hypothesis^{1,2} of baryogenesis at the electroweak phase transition in the minimal standard model. To overcome these difficulties attention has been given to extensions of the minimal standard model, involving the addition of extra scalars^{3,1,4}. Prominent among these is the minimal supersymmetric standard model, MSSM, where the Higgs sector is just two doublets^{5,6}. Here we shall discuss, with a perturbative treatment, the next-to-minimal model, NMSSM, which has additionally one singlet Higgs scalar⁵. In the absence of hard information we have to adopt a hypothesis on the SUSY breaking scale and on the spectrum of the particles, and ours is the simplest possible. We follow a number of papers of recent years in taking the SUSY breaking scale, M_S , to be of the order of 1 TeV; we take perfect supersymmetry above that scale. Then at M_S the quartic scalar couplings are fixed by the gauge couplings and two more parameters. We then use the renormalization group equations to run down the quartic couplings to the electroweak scale, where we investigate the nature of the phase change. There are also cubic and quadratic supersymmetry breaking couplings, and there results a space of variable parameters in which we investigate what proportion leads to a first order electroweak phase change, and so is compatible with electroweak baryogenesis.

There has been quite considerable previous work on the electroweak phase change in the MSSM. We are not aware of so much on the NMSSM. The work of Pietroni⁷ has pointed up that the NMSSM, in contrast to the MSSM, has cubic terms in the scalar field potential at tree level leading to the possibility of a potential barrier in radial directions even at tree level. That work uses a unitary gauge which we consider to be not so secure a basis for the consideration of phase changes as the Landau gauge which we use^{8,4}.

We start with the tree level potential, which is⁵

$$V_0 = \frac{1}{2}(\lambda_1(H_1^\dagger H_1)^2 + \lambda_2(H_2^\dagger H_2)^2) + (\lambda_3 + \lambda_4)(H_1^\dagger H_1)(H_2^\dagger H_2) - \lambda_4 \left| H_1^\dagger H_2 \right|^2 + (\lambda_5 H_1^\dagger H_1 + \lambda_6 H_2^\dagger H_2)N^* N + (\lambda_7 H_1 H_2 N^{*2} + hc) + \lambda_8 (N^* N)^2 + (|\mu|^2 + (\lambda\mu^* N + hc))(H_1^\dagger H_1 + H_2^\dagger H_2)$$

$$+ m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 N^* N - ((m_4 H_1 H_2 N + \frac{1}{3} m_5 N^3 - \frac{1}{2} m_6^2 H_1 H_2 - m_7^2 N^2) + hc)$$

where $H_1^T = (H_1^0, H_1^-)$, $H_2^T = (H_2^+, H_2^0)$, and $H_1 H_2 = H_1^0 H_2^0 - H_1^- H_2^+$. The terms involving μ arise from the μ term in the superpotential. The last two lines comprise all possible soft supersymmetry breaking terms⁵. V_0 is a function of 10 real scalar fields, $\phi = \phi_1, \phi_2, \dots, \phi_{10}$, 4 for each of the Higgs doublets and 2 for the singlet, N .

For simplicity, and to automatically ensure real VEVs, we shall follow the usual practice and take the parameters real. The boundary values at M_S of the quartic couplings are given by⁹

$$\lambda_1 = \lambda_2 = \frac{1}{4}(g_2^2 + g_1^2), \lambda_3 = \frac{1}{4}(g_2^2 - g_1^2), \lambda_4 = \lambda^2 - \frac{1}{2}g_2^2,$$

$$\lambda_5 = \lambda_6 = \lambda^2, \lambda_7 = -\lambda k, \lambda_8 = k^2$$

and are developed down to M_{Weak} by using the appropriate RG equations⁹. λ and k , from the superpotential, are free parameters at M_S ⁵. However they are linked to the one important Yukawa coupling^a, g_t , by 3 simultaneous RG equations⁹; in developing from high energy down to M_S their values there should not be such that they correspond to divergent or unnaturally large values at high energy. The m_1^2, m_2^2, m_3^2 are standard mass parameters and are to be specified in terms of the VEVs and other parameters by the usual requirement that $V_0(\phi)$, $\phi = \phi_1, \phi_2, \dots, \phi_{10}$, with the parameters λ_i assumed renormalised at the electroweak scale, be a minimum at the neutral VEVs:

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \langle N \rangle = x \quad (1)$$

where v_1, v_2 and x are real and $v = \sqrt{v_1^2 + v_2^2} = 174 \text{ GeV}$. The scalar mass-squared matrix gives rise to 7 massive physical particles and 3 zero mass would-be Goldstone bosons. We can now discuss the other parameters in V_0 .

Firstly there are the terms involving μ which arise from the μ term in the superpotential. This raises the μ -problem (first noted in the MSSM)¹⁰; μ would naturally be expected to take on a value of the order of magnitude of the fundamental scale of the theory, whereas

^aWe are not considering large $\tan\beta$ here

phenomenologically it should be of the order of the other electroweak terms. We do not take the point of view that the NMSSM can solve this by its having largely phenomenologically equivalent terms in the N field and simply setting $\mu = 0$ ⁹. This can have its own difficulties when a resulting Z_3 symmetry gives rise to domain walls¹⁰. We tolerate the mu-problem. It should be noted that we have extra Z_3 breaking by the phenomenological term $m_6^2 H_1 H_2$. Secondly there are the remaining soft parameters m_4, m_5, m_7^2 ; their provenance as completing the most general NMSSM breaking V_0 was given in Ref.⁵.

Going now to the T-dependent terms in the effective potential we proceed in the usual way by the loop expansion. For a temperature sufficiently high compared to the masses we use the well known expansion in descending powers of temperature down to the logarithmic term. We include the 1-loop contribution of the Higgsinos in the case where the masses of the winos and binos are taken large, of order M_S . The size of the parameters gives these Higgsinos masses to be significantly less than M_S and thus they should be taken into account; the only quark included is the top. We also modify the 1-loop calculation by including ring diagrams, and suppressing gauge boson longitudinal polarization excitations². For smaller T we use a Boltzmann suppressed form³ for the effective potential.

2 Results

Calculations with the kinetic equations for the dilution of baryonic charge just after the phase transition give a baryon preservation condition^{1,2}

$$\frac{v(T_{crit})}{T_{crit}} \geq \xi \quad (2)$$

where ξ varies between about 0.9 and 1.5 according to the gauge and other couplings of the theory. We take $\xi = 1$. In practice in various theories just two criteria have been used to find the critical temperature, T_{crit} , and authors have made a choice of either one or the other; we use both and compare. One is the temperature, T_0 , at which, for decreasing T, the curvature of the effective potential $V(\phi, T)$ at $\phi = 0$ (assumed to be the previous global minimum) first vanishes in the Higgs doublet neutral field directions. The other is the temperature, T_C , at which the value of V at a minimum with a markedly non-zero v' first becomes the global minimum of $V(v'_1, v'_2, x', T)$. We note that the term in μ in V_0 gives rise to a term in $V \propto T^2 \lambda \mu N$ whose existence means that the origin cannot be a minimum. Thus only for $\mu = 0$ is the first criterion, $T_{crit} = T_0$, applicable. Now the shape of V depends on the theory parameters:- $[\mu, \lambda, k]$; $[v = 174 \text{ GeV}, \tan\beta = \frac{v_2}{v_1}, x]$ (replacing m_1^2, m_2^2, m_3^2); $[M_{ch}]$ (mass of charged Higgs, replacing m_4); $[m_5, m_6^2, m_7^2]$.

In the work reported here we have adopted the values of Ref.⁽⁹⁾ in taking $k = .1, \lambda = .65$. For other parameters we have searched in the regions $1 < \tan\beta < 3, 200 < M_{ch} < 300 \text{ GeV}, -5 < \frac{m_6^2}{50^2} < 5, -5 < \frac{m_7^2}{50^2} < 5, -1 < \frac{m_5}{50} < 1$, while for x we have used $x=174 \text{ GeV}$, having found that values significantly bigger or smaller greatly restricted the range of the other parameters compatible with the T=0 criteria. Considerations on the special parameter μ are given below, where we now outline our current results:

1. $\mu = 0$: A search over a grid of 200,000 sets of parameters found a basis space of about 20,000 giving an acceptable broken T=0 electroweak vacuum. The curvature criterion gave about 10% of this basis space compatible with baryon number preservation with $T_{crit} = T_0$ mostly in the range 50-150 GeV. The lightest Higgs scalar was of the order of 100 GeV, and the lightest Higgsino was of a similar mass.

Around 80% of these acceptable cases were also acceptable on the equal minimum criterion, $T_{crit} = T_C$, though with a somewhat different T_{crit} , the difference being as much as 50 GeV in a few cases. On the average T_C is 10 GeV greater than T_0 .

2. $\mu \neq 0$: In the region close to the previous successful cases, sets of parameters exist with values of μ of magnitude up to 40 GeV with negative values preferred.

3. Conclusions: We confirm, and quantify, previous results that electroweak baryon preservation is compatible with the NMSSM and we additionally find that a μ parameter of moderate magnitude is acceptable.

The investigation of the parameter space is not complete and is continuing.

3 References

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